

The morphology and luminosity function of the Galactic bulge from TMGS star counts

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ABSTRACT

The bulge of the Galaxy is analysed by inverting K -band star counts from the Two-Micron Galactic Survey in a number of off-plane regions. A total area of about 75 square degrees of sky is analysed. Assuming a non-variable luminosity function within the bulge, we derive the top end of the K -band luminosity function and the stellar density function, whose morphology is fitted to triaxial ellipsoids.

The luminosity function shows a sharp decrease brighter than $M_K = -8.0$ when compared with the disc population. By fitting ellipsoids, we find that the bulge is triaxial with the major axis in the plane at an angle with line of sight to the Galactic centre of 12° in the first quadrant. The axial ratios are $1 : 0.54 : 0.33$ and the distance of the Sun from the centre of the triaxial ellipsoid is 7860 pc.

The best fit for the stellar density, assuming an ellipsoidal distribution, is $D(t) = 1.17(t/2180)^{-1.8} \exp(-(t/2180)^{1.8})$ stars pc⁻³, for $1300 < t < 3000$, where t is the distance along the major axis of the ellipsoid in parsecs.

Key words: Galaxy: structure — infrared: stars — Galaxy: stellar content

1 INTRODUCTION

Among the many aspects of the bulge of the Galaxy that are still unknown, mainly because of the high extinction due to interstellar gas and dust, is the near-infrared luminosity function, knowledge of which is provided only by observations in Baade's window (Frogel & Whitford 1987; Davidge 1991; De Poy et al. 1993; Ruelas-Mayorga & Noriega-Mendoza 1995; Tiede,

Frogel & Terndrup 1995). In the visible, Gould (1997) uses the *Hubble Space Telescope* V and I bands. However, from extrapolation from Baade's and other clear windows to the whole bulge may not be appropriate, in particular because these are 'special' regions. Furthermore, these regions are very small, containing relatively few stars, and hence give very poor statistics at the brighter magnitudes. The bright end of the luminosity function is very important in order to determine the age of the population.

Many authors find non-axisymmetry in the Galactic bulge (Weiland et al. 1994; Feast & Whitelock 1990 ; etc.) with a negligible out-of-plane tilt (Weiland et al. 1994) and giving more counts in the positive galactic longitudes than in the negative ones. However, other authors (Ibata & Gilmore 1995) claim that axisymmetry is suitable.

This paper examines the K distribution of bulge sources in the Two-Micron Galactic Survey (TMGS) though the inversion of the fundamental equation of stellar statistics using Lucy's algorithm (Lucy 1974).

2 STAR COUNTS AND INVERSION PROCEDURE

The K -band star counts are from the TMGS (Garzón et al. 1993), which has covered about 350 square degrees of sky and detected some 700000 sources in or near the Galactic plane. The survey has a completeness limit in the bulge region of $m_K \approx +9.0$, except for the regions near the Galactic centre where confusion reduced this by about half a magnitude.

For this study we use 71 regions in the Galactic bulge ($10^\circ > |b| > 2^\circ$, $|l| < 15^\circ$) taken coming from strips with $\delta = -30^\circ$, $\delta = -22^\circ$ and $\delta = -16^\circ$. The TMGS strips are at constant declination, which means that they cross the Galactic plane at a significant angle; hence the three strips sample a wide range of lines of sight through the bulge. The total sky coverage is some 75 deg^2 of sky. The area near the Galactic plane was not used in order to avoid components which belong neither to the bulge nor to the disc (e.g. spiral arms) and the high and variable extinction close to the plane. The outer limits were set so that the bulge-to-disc stellar ratio was still acceptable, i.e. there are enough bulge stars in comparison with disc stars.

In the areas considered, the contribution to the star counts will be primarily from the disc and bulge. In order to isolate the bulge component a model disc was subtracted from the total counts. The model developed by us was based on Wainscoat et al. (1992), which has been used because it provides a good fit to the TMGS counts in the region where the

disc dominates (Cohen 1994b; Cohen et al., in preparation). The revision to Wainscoat et al. (1992) given in Cohen (1994a) does not significantly alter the form of the disc in the area of interest. It was also expected that the model would give an adequate fit for the bulge counts; this, however, was not the case.

For each of the 71 regions, centred on Galactic coordinates $(l, b)_i$, where i is the field number, the cumulative stellar star counts towards the bulge, N_K , expressed in rad^{-2} , follows

$$N_{K,\text{bulge}}(m_K) = N_K(m_K) - N_{K,\text{disc}}(m_K) = \int_0^\infty \Phi_{K,\text{bulge}}(m_K + 5 - 5 \log_{10} r - a_K(r)) D_{\text{bulge}}(r) r^2 dr, \quad (1)$$

where $\Phi_{K,\text{bulge}}(M) = \int_{-\infty}^M \phi_{K,\text{bulge}}(M) dM$, ϕ is the normalised luminosity function ($\int_{-\infty}^\infty \phi(M) dM = 1$), D is the density, and a_K is the extinction in the line of sight. For the extinction we have followed Wainscoat et al. (1992), who assume that the extinction has an exponential distribution with the same scale length as the old disc and a scale height of 100 pc. This is normalised to give $A_K = \frac{da_K}{dr} = 0.07 \text{ mag kpc}^{-1}$ in the solar neighbourhood. As the areas of interests are off the plane the extinction to the bulge sources is between 0.05 to 0.5 mag at K . Garzón et al. (1993) showed that, away from the plane, the K extinction varies smoothly and has little effect on the distribution of the star counts. In fact, the TMGS histograms in Garzón et al. (1993) off the plane show that the extinction cannot be patchy.

With the change of variables $\rho_K = 10^{0.2a_K(r)} r$ and $\Delta_K = D(r) \frac{r^2 dr}{\rho_K^2 d\rho_K}$ we transform the equation (1) of counts in the bulge into

$$N_K(m_K) = \int_0^\infty \Phi_K(m_K + 5 - 5 \log_{10} \rho_K) \Delta_K(\rho_K) \rho_K^2 d\rho_K. \quad (2)$$

The density is obtained by inverting this equation: Δ is the unknown function and Φ is the kernel of a Fredholm integral equation of the first kind (see Trumpler & Weaver 1953, p. 96).

When the luminosity function Φ , is the unknown instead of Δ , then we can make a new change of variable $M_K = m_K + 5 - 5 \log_{10} \rho_K$ and we obtain a new first kind of Fredholm equation:

$$N_K(m_K) = 200(\ln 10) 10^{\frac{3m_K}{5}} \times \int_{-\infty}^\infty \Delta_K(10^{\frac{5+m_K-M_K}{5}}) 10^{\frac{-3M_K}{5}} \Phi_K(M_K) dM_K, \quad (3)$$

where Φ is now the unknown function and Δ_K is the kernel.

Both integral equations are inverted using Lucy's statistical method (Lucy 1974). This method is fairly insensitive to the high-frequency fluctuations and in our tests with known

functions, which are similar to that of the bulge, gave good results (note: this method would not be applicable to the disc as a whole).

The above equation can be solved for either the luminosity function or the density function, but not both simultaneously. A simple comparison of the Wainscoat et al. (1992) model with the TMGS counts suggested that while there were problems with the bulge luminosity function, the density function gave an adequate starting value for the iteration. Therefore it was decided to solve first for the average luminosity function using the Wainscoat et al. (1992) bulge density.

We have made the assumption that the luminosity function is independent of the position. This assumption is suspect (see Frogel 1988, section 3) since the observed metallicity gradient might affect the luminosity of an AGB star, although not the non-variable M-giants whose bolometric luminosity function is nearly independent of the latitude (Frogel et al. 1990). Some authors claim that there is a population gradient (Houdashelt 1996), whilst others do not (Ibata & Gilmore 1995, who argue that there is no detectable abundance gradient in the Galactic bulge over the galactocentric range from 500 to 3500 pc). While our assumption may not be strictly true, it is still a reasonable approximation. We, therefore, assume that the variation of the bulge luminosity function in between about 250 pc and 1200 pc from the galactic plane is small.

With this averaged luminosity function, we inverted (2) to derive a new density distribution. In this step we used the 37 regions with the highest counts as the determination of the density is more sensitive to noise. The inversion of the luminosity function is more stable because the density distribution is sharply peaked and so the kernel in (3) behaves almost as a Dirac delta function: the shape of the density distribution does not significantly affect the shape of the luminosity function. The new density was then used to improve the luminosity function, etc. The whole process was iterated three times which was enough for the results to stabilize as can be seen in the Fig. 1: we see how the result of the third iteration is very close to the first; i.e. stabilization is reached in the first iterations.

The functions of interest are ϕ , the derivative of Φ , and D , related to Δ by the change of variable expressed above.

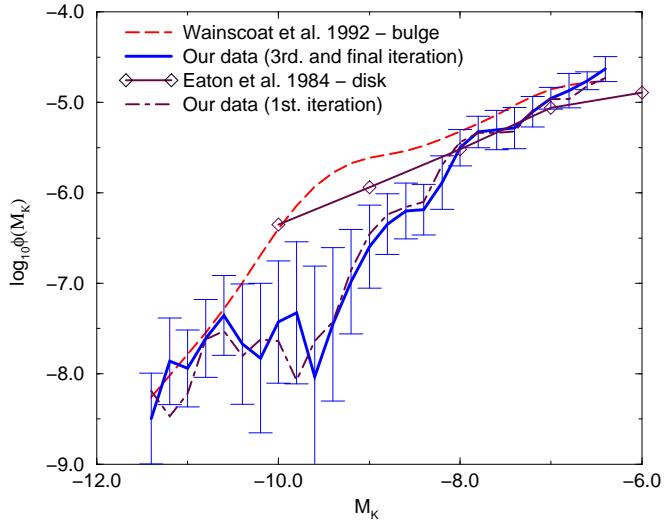


Figure 1. Luminosity function of the bulge stars in the K band: the thick solid line is the third and final iteration. Comparisons with the same luminosity function in the first iteration, Wainscoat et al. (1992) in the bulge and Eaton, Adams & Gilels (1984) in the disc are also provided.

3 THE TOP END OF THE K LUMINOSITY FUNCTION

After three iterations the luminosity function was independent of the position $(l, b)_i$ and stable. The obtained luminosity function is shown in the Fig. 1. The coincidence of our luminosity function with that of Wainscoat et al. (1992) for the faintest stars is due to the fact that we used their luminosity function to initiating the iteration process. Practically speaking, this overlapping corresponds to an effective normalization to the Wainscoat et al. (1992) luminosity function in the range $M_K > -7$.

Fig. 1 shows that for $-10 < M_K < -7$ the bulge luminosity function is significantly lower than that of the disc (Eaton, Adams & Gilels 1984). Hence, the density of very bright stars in the bulge is much less than in the disc. Fainter than $M_K = -7$ the luminosity functions of the disc and the bulge coincide, in agreement with Gould (1997). The luminosity function for $-10 < M_K < -7$ is significantly below the synthesized luminosity function assumed by Wainscoat et al. (1992) for the bulge in their model of the Galaxy. The discrepancy could arise from their not having taken into account that the brightest stars in the bulge are up to 2 magnitudes fainter than the disc giants (Frogel & Whitford 1987). This would shift the luminosity function to the right.

Comparison with bolometric luminosity function obtained by other authors (see references in the introduction) is not possible since we do not have the bolometric corrections.

Also, in most of cases the magnitude interval is different. Tiede, Frogel & Terndrup (1995) provide, by combining data from different articles, the luminosity function in the K -band as a function of the apparent magnitude in the range $5.5 < m_K < 16.5$. The brightest magnitudes are taken from Frogel & Whitford (1987). The comparison with our luminosity function is not direct since they have not normalized their luminosity function to unity; moreover, they have not taken into account the narrow but non-negligible dispersion of distances. In Fig. 16 of Tiede, Frogel & Terndrup (1995) there is a fall-off of the luminosity function for $m_K \leq 6.5$ or in Fig. 18 of Frogel & Whitford (1987) for $M_{bol} \leq -4.2$, which could be comparable with that of our luminosity function at $M_K \approx -8.0$. However, because of the far larger area covered by the TMGS, the error for the brightest magnitudes is far lower in this paper, the result being pushed well above the noise; this is not the case for Frogel & Whitford (1987).

The presented luminosity function for very bright stars (lower than $M_K \sim -9.5$) is of low accuracy. The number of bulge stars in this range is very small, small errors due to contamination from the spiral arms will mean that the luminosity function is overestimated.

The bulge is older than the disc. However, the comparison with the halo globular clusters ages remains open. These data could help to investigate the age of the bulge by comparison with theoretical models of stellar evolution.

4 BULGE MORPHOLOGY

The morphology of the bulge can be examined by fitting the isodensity surfaces to $D(\vec{r}) = D(r, l, b)$. We fitted three-dimensional ellipsoids to 20 isodensity surfaces (from 0.1 to 2.0 star pc $^{-3}$, in steps of 0.1) with four free parameters: R_0 , the Sun-Galactic centre distance (the ellipsoids are then centred on this position); K_z and K_y , the axis ratios with respect the major axis x ; and α the angle between the major axis of the triaxial bulge and the line of sight to the Galactic centre (α between 0° and 90° is where the tip of the major axis lies in the first quadrant). These ellipsoids have two axes in the Galactic plane, (x and y) and the z axis which is perpendicular, we have ignored a possible tilt out of the plane.

The four averaged parameters have been fitted for the 20 ellipsoids and the results are:

$$R_0 = 7860 \pm 90 \text{ pc}$$

$$K_z = 3.0 \pm 0.9$$

$$K_y = 1.87 \pm 0.18$$

$$\alpha = 12 \pm 6 \text{ deg.}$$

We can also express the axial ratios as $1 : 0.54 : 0.33$. The errors are calculated from the average of the ellipsoids, and so do not include possible systematic errors (for example: subtraction of the disc, contamination from other components, procedure of the inversion,...). Hence, the true errors are larger than stated but tests suggest that they do not alter the general findings of this paper. These numbers indicate that the bulge is triaxial with the major axis close to the line of sight towards the Galactic centre. The error in K_z is quite large and is due to a non-constant axial ratio of the ellipsoids. There is a trend towards increasing K_z with proximity to the centre, i.e. the outer bulge is more circular than the inner bulge.

In general the result presented here are in agreement with those from other authors. The projection of an ellipsoid of the above characteristics on to the sky, as viewed from the position of the Sun, gives an ellipse with axial ratio 1.7 ± 0.5 (i.e. $1 : 0.58$). This is compatible with the value of $1 : 0.6$ obtained by Weiland et al. (1994). Dwek et al. (1995) give higher eccentricity values for the axial ratios ($1 : 0.33 : 0.22$), but the angle $\alpha = 20 \pm 10$ deg is compatible with the value given here. From the dynamic model, assuming a gas ring in steady state, Vietri (1986) finds axial ratios of $1 : 0.7 : 0.4$, which are close to our result. Binney et al. (1991) find $\alpha = 16$ deg. for a bar, i.e. a triaxial structure in the center of the Galaxy, in order to explain the kinematics of the gas in the center of the Galaxy.

The distance R_0 derived here is slightly less than that used in the model of the disc. However, the small changes in R_0 can be compensated by small changes in the other model parameters, such as the scale length, so that the predicted counts remain the same. As the model used already gave a good fit to the disc, we decided not to make *ad hoc* modifications to account for a smaller R_0 since the disc is not the subject in this paper.

The values for the distance from the Sun to the Galactic centre is very close to the currently accepted value of just under 8 kpc (see Reid, 1993 for a review). Recent estimates range from 7.1 ± 1.5 kpc (Reid et al. 1988) to 8.1 ± 1.1 kpc (Gwinn, Moran & Reid 1992).

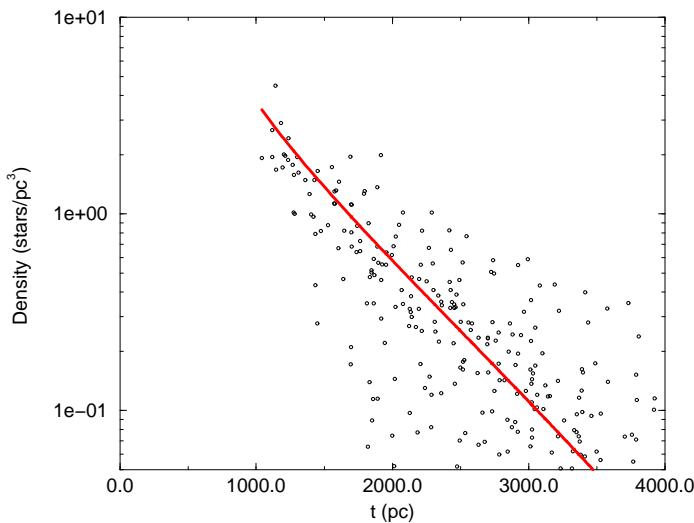
5 BULGE STELLAR DENSITY DISTRIBUTION

The galactocentric distance along the major axis for different isodensity ellipsoids, with the averaged parameters, is

$$t = \sqrt{x^2 + K_y^2 y^2 + K_z^2 z^2} \quad (4)$$

Table 1. Relationship between the maximum distance of the ellipsoid and the bulge star density.

t (pc)	D (pc $^{-3}$)	t (pc)	D (pc $^{-3}$)
3020 ± 810	0.1	1620 ± 250	1.1
2630 ± 650	0.2	1580 ± 240	1.2
2420 ± 590	0.3	1540 ± 240	1.3
2230 ± 490	0.4	1460 ± 230	1.4
2120 ± 450	0.5	1420 ± 230	1.5
1990 ± 380	0.6	1390 ± 230	1.6
1900 ± 350	0.7	1380 ± 240	1.7
1840 ± 330	0.8	1360 ± 250	1.8
1720 ± 280	0.9	1360 ± 260	1.9
1670 ± 270	1.0	1320 ± 220	2.0

**Figure 2.** Fit of the density distribution. The solid line is the best fit.

and the distance along the minor axis is t/K_z . The relationship between the distance t and the density is given in Table 1.

A power law with exponent -1.8 is observed in the centre of the bulge and also in other galaxies (see review in Sellwood & Sanders 1988). When the density function $D(t)$ is fitted to $D(t) = A(t/t_0)^{1.8} \exp(-(t/t_0)^\gamma)$, with γ , t_0 and A as free parameters we obtain (t in pc)

$$D(t) = 1.17(t/2180)^{-1.8} \exp(-(t/2180)^{1.8}) \text{ stars pc}^{-3}.$$

This gives us an estimate of the fall-off of the density between 1.3 and 3.0 kpc from the centre in the direction parallel to the major axis or between 0.4 and 1.0 kpc in the direction perpendicular to the plane. As can be seen in Fig. 2, the dispersion of points around this law is large, so it is possible to accommodate other functions or a different parameter set. A different luminosity function would change the amplitude of the stellar density. If

the normalization for the luminosity function were incorrect then the multiplication factor needed for the luminosity function would be used to divide the star density.

6 CONCLUSIONS

We have found that a) the relative abundance of the brightest sources in the bulge ($M_K < -8.0$) is much less than in the disc; b) the bulge is triaxial with the major axis nearly along the line of sight to the Galactic centre, the best fit giving a value of 12 degrees shifted to positive Galactic longitudes in the plane; and finally the stellar density drops quickly with distance from the Galactic centre (i.e. the density distribution is sharply peaked). The -1.8 power-law observed at the Galactic centre needs to be multiplied by an exponential to account for the fast drop in density in the outer bulge.

The procedure used here is rather different from that of those authors who fit the parameters directly to the star counts. First, we have inverted the counts. Then, once we have the luminosity function and density distribution in which the approximate ellipsoidal shape was evident, the parameters could be fitted for each isodensity surface. Assuming an ellipsoidal bulge with constant parameters for all isodensity regions and fitting these parameters to the counts is less rigorous since there is no *a priori* evidence for this assumption. In fact our method suggest that constant parameters for the ellipsoids do not give the best fit for the density $D(\vec{r})$. Instead, a decreasing $K_z(t)$ would provide the best results.

All these aspects will be developed with further details in a future paper, where we shall explore the details and limitations of the inversion and the variation of K_z .

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